NOTES ON PRINCIPLES OF OIL ACCUMULATION[1]

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Petroleum deposits of commercial importance occur in sedimentary rocks. The great majority of such deposits in the mid-continent field are found in sands or in thin-bedded porous limestones with intervening shales. These shales are generally dark colored, often black, and carry bands of highly bituminous material. Paying amounts of oil have not been found in very thick sandstones or limestones without notable shale "breaks,"[2] or without being closely associated with shale horizons. Even the Bartlesville, the thickest pay sand of the region, shows many black shale partings when the cuttings of each screw are examined carefully.

The examination of a number of such cuttings in the proximity of many different oil sands throughout the mid-continent field reveals the fact that black bituminous shales are invariably present.[3] These beds are often described by the drillers as coal, asphalt, or black lime, according to the hardness and appearance of the material. The shales are typical oil shales, quite similar in character to those of Colorado and Utah. The bituminous material occurs in solid form as none of the ordinary solvents show coloration after solution tests. Upon distillation, such shales have given off petroleum-hydrocarbons. The sands are entirely barren of such compounds.

Before concentrations of petroleum can take place, it is necessary that this solid organic gum called kerogen be changed so that liquid hydrocarbons are formed. Such a change has com-

[1] Published through courtesy of the Empire Gas and Fuel Company.

[2] Drillers are accustomed to speak of thin changes in a thick formation as "breaks."

[3] In cuttings examined to date the one exception to this statement is the Hoy (1,100 feet) sand of the Garber, Oklahoma, field.

monly been made in the laboratory by heating. However, the majority of oil deposits are located in the upper 3,000 feet of sediment, and evidence that the necessary distillation temperature of 450° F. has ever been reached at such places is quite lacking. Oil-field waters of this region are seldom above 100° F. in temperature, ranging generally from 80 to 90° F. Consequently it is difficult to explain the reduction of liquid oil from bituminous shales by heat, except possibly in very limited local areas of intense friction. Even in such cases the amount of heat is highly problematical.

The other most important factor below the surface of the earth is pressure. Pressure alone can cause no change in this material when the included water is not allowed to escape, and the shales are only compacted when the water is given free passage.

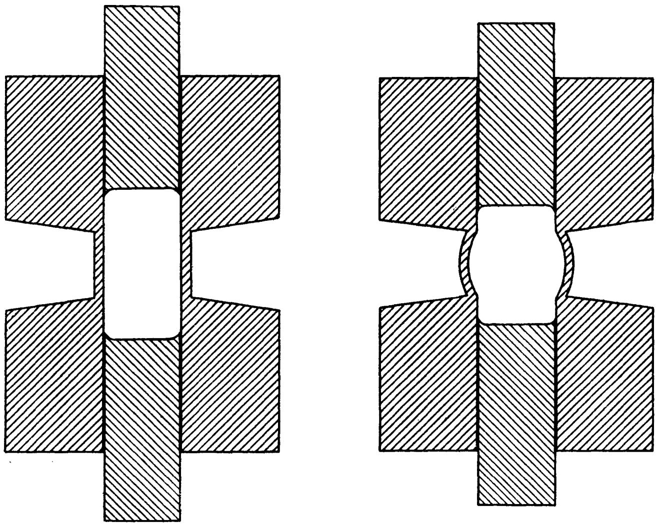
These facts led to a laboratory investigation of rock flowage upon the hypothesis that the mechanical energy or work done upon the shale by applying a force through a distance would accomplish the same results as the equivalent amount of heat energy. The experiment was carried out by Mr. E. A. Trager and the author, similar to the experiments of Adams and Bancroft.[1]

1. *Description of flowage experiment.*—Cylindrical steel bars (Fig. 1) were sawed in lengths of about 3 inches and bored into tubes having an inside diameter of 2 cm. The thickness of the walls in the center of the cylinders was reduced to 0.25 cm. Pistons of steel were turned to fit the tubes. Cylindrical pieces of an oil shale (yielding 25 gallons per ton and having a crushing strength of about 3,000 pounds per square inch) were cut into 1-inch lengths and placed in the center of the tubes, where the thickness of the walls was reduced. The pistons were then inserted on either side of the shale cylinder and pressure was applied to them in a Riehle compression machine, thus squeezing the shale and eventually bulging the tubes in the center. By so doing, the shale was made to flow. No appreciable amount of heat was was developed. Solution tests taken before the experiment gave no indication of liquid hydrocarbons, while those taken after flowage with the same shale gave strong coloration. In some cases, after the experiment small globules of oil could be seen in the shale with a hand lens. The steel tubes necessitated

[1] Adams and Bancroft, "On the Amount of Internal Friction Developed in Rocks during Deformation and on the Relative Plasticity of Different Types of Rocks," *Jour. Geol.*, XXV, 597.

such a great pressure to make the bulging that tubes of brass and softer metals were tried. The results were substantially the same. Details of this work will be described in some later paper.[1]

The experiment is referred to here in order to show how liquid hydrocarbons may be formed in the shales from the solid bituminous material at ordinary temperatures and under pressures of 5,000 to 6,000 pounds, such as exist at the depth of oil-bearing horizons; and that the only places where such compounds would be formed are in areas of differential movement.



BEFORE COMPRESSION AFTER COMPRESSION

FIG. 1.—Longitudinal section through steel cylinder inclosing rock column

After the oil is once formed in the shales, it is collected in the porous zones by water. The action is one commonly called "Capillary Concentration."[2] Water, having a greater surface tension and adhesion for shale particles than oil, moves into the smaller openings of the shale, and the oil is thus forced into the larger openings of the porous water horizons. Before this can take place, the water sand or reservoir rock must come in direct

[1] Unpublished manuscript of E. A. Trager and the author.

[2] C. W. Washburne, *American Institute Mining Engineers*, 1914, p. 830.

contact with the oil-soaked shale. Oil shales are usually separated from sand or porous rock by barren shales. These overlying and underlying a water stratum would be saturated with capillary water, and it would be impossible for oil to migrate through even a very thin water shale, for reasons stated later. It then becomes necessary for breaks in the intervening shale to occur so that the water may come in direct contact with the oil-soaked horizon. Such conditions can be brought about only by faulting or jointing. A very small displacement or a slight open joint may give the water from large openings a chance to

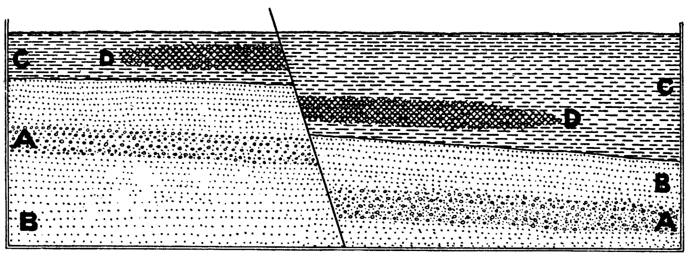


FIG. 2.—Diagram of apparatus for accumulation experiment before partition was removed, showing oil in shale marked "D."

enter the oil-soaked shale and the oil to exchange places with the water. To substantially back these statements, the following experiment is offered:

2. *Description of accumulation experiment.*—A water-soaked sand bed (*B*) two inches thick was placed in a glass box 18 in. by 6 in. by 6 in. (Fig. 2). In the center of the box a celluloid sheet partition was set at a slight angle to the vertical and effectively sealed to the sides and bottom of the box with putty. Each division of the box was then water-tight. The sand bed was built higher on one side of the partition than on the other; the beds on each side of the partition were slightly sloping in the same direction, representing a normal fault. About one inch below the top of the sand bed was a thin layer of coarser sand (*A*) running uniformly throughout. Water-soaked mud (*C*) from ground shale (passing a 200-mesh sieve) was placed above the sand. This layer was about one inch thick. Then a one-inch layer of oil-soaked mud (*D*) was built over the area adjoining the celluloid partition, but not extending to the corners of the box. The reason for not covering the entire area with oil-soaked shale was to avoid the fittings around the corners as a perfect seal is hard to accomplish in corners of such a small box. The

remainder of the box was filled with water shale. Each formation had the corresponding displacement on either side of the partition. The box was allowed to stand for twenty-four hours. No movement of the oil was noticeable after that time. The celluloid partition was then carefully pulled out so that the beds were undisturbed and the softer beds of the shale immediately closed the small opening left by the removal of the sheet. Within one hour from this time oil began to collect in the porous layer of the sand. This continued for several hours until the porous sand was nearly filled on each

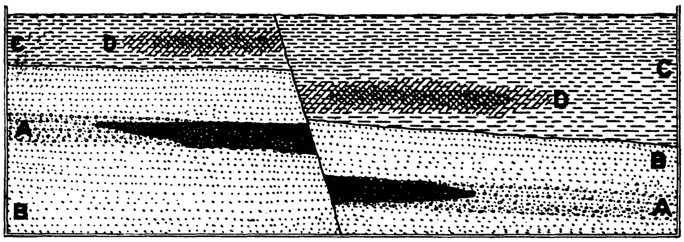


FIG. 3.—Diagram of apparatus for accumulation experiment after partition was removed, showing oil partially replaced from "D" and accumulated in "A."

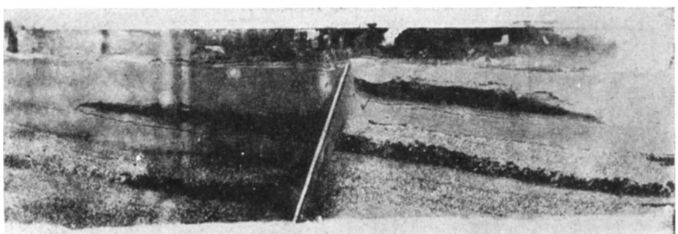


FIG. 4.—Photograph of apparatus used in Experiment 2, showing the accumulation of oil in the sand.

side of the represented fault (Fig. 3). Capillary water partially had replaced the oil in the original oil-soaked shale and had sealed the remaining oil completely in the center of the shale body. After the oil had come to an equilibrium in the sand, it did not move apparently up the dip but remained in the porous zone surrounded by water. The relative position of oil and water was stationary until the experiment was torn down two weeks later. Note photograph shown in Fig. 4.

The foregoing evidence shows that liquid petroleum in shale cannot move into the porous water horizons until the intervening

barren shales are opened by joints or the oil shale layer faulted against water strata.[1]

Capillary action is very slightly increased with the increase of pressure,[2] consequently the movements underground are not materially different from those in the laboratory. The action, however, varies with the absolute temperature of the liquids, but in the upper 5,000 feet of sediment the temperatures would not alter the actions as described.

When the oil once reaches the sand or porous zone, it adjusts itself to occupy the larger openings and remains there indefinitely unless disturbed by some outside factor.

It is impossible for oil to migrate any great distance in the oil-bearing formations of the mid-continent field. A discussion of this point is taken up in three parts: (1) difficulty of migration from the mechanical standpoint; (2) negative experimental evidence; (3) evidence of lenticular character of water zones.

The movement of oil in water-soaked sediments is almost entirely a problem of surface tension. Water, having a greater surface tension and attraction for rock surfaces than oil, moves into the smaller pores occupied by the oil and forces it into larger openings. Such movement is characteristic as long as the openings are less than 0.1 mm. Where the sand grains are unusually large (3 mm. in diameter or over) or where induced openings have been made locally in some hard formation, sorting due to specific gravity is free to take place if the unbalanced weight overcomes the friction of the movement.

Relative forces thus affecting oil movement can be figured from the size of the openings in the rocks.[3] In a shale at a depth of 1,500 feet, where openings are 0.01 micron, the capillary force

[1] It is the popular belief that faults are detrimental to oil accumulation since they afford passages for upward migration of oil, thereby allowing the oil to escape. Such may be the case occasionally where the formations stand open along the fault plane for hundreds of feet. In the oil fields of Oklahoma most faults probably never reach the surface. Shales being so predominant in the section invariably fall together along the fault plane, thus tightly sealing the majority of faults so that they are not generally conductors of oil upward.

[2] Johnston and Adams, *Jour. Geol.*, XXII, 9.

[3] *Ibid.*, p. 13.

of the water to replace the oil is about 1,400 lbs. per square inch;[1] the unbalanced force due to specific gravity is less than 0.1 lb. per inch; and frictional resistance is probably a fraction of a pound per square inch. As the openings become larger the capillary-expelling force of the water becomes less and when these have reached 0.5 mm. this force is zero. Then the unbalanced specific gravity and fractional resistance are the only forces to be accounted for. Such places are only local in the sedimentary series, and the great majority of openings in oil-bearing formations are much smaller. The force necessary to make oil migrate through a wet shale (openings 0.01 micron) for a depth of 1,500 feet is about 4,000 lbs. per square inch. This is about 1,500 lbs. per square inch greater than the combined rock and complete hydrostatic pressure. Consequently, it is utterly useless to assume migration of oil through wet shale. Even when the openings in a sandstone are as much as 0.1 mm. in diameter, the capillary resistive power is about 0.4 lb. per square inch compared with 0.1 lb. per inch, the unbalanced force due to specific gravity. The instant an oil particle (migrating in water sediments) reaches a series of openings larger than those surrounding it, it stops and remains there indefinitely, as long as these surrounding openings are less than 0.1 mm. All sandstones are irregular and a series of openings larger than 0.1 mm. is never very extensive.

3. *Experiment on migration of oil in wet sand.*—A water-soaked (20-mesh) sand bed with a 20° slope was placed in a glass box 18 in. by 6 in. by 6 in. (Fig. 5). Near the lower end of the stratum a small volume of larger (10-mesh) sand grains was filled with oil and covered with water-soaked shale. This was allowed to remain for one week and no movement of the oil had taken place. Then glass tubes were inserted into the sand at either end of the box. Water was pumped out of tube No. 1 at the higher end of the sand bed and at the same time water was allowed to run into tube No. 2 at the lower end. This was continued until the amount of water forced through the sand was several times its volume. No movement of the oil resulted. The accompanying photograph, Fig. 6, was taken after the experiment.

[1] These figures are rough approximations from data of Johnston and Adams (*ibid.*); also Harkins, Davies, and Clark, *Journal American Chemical Society*, XXXIX, No. 4 (April, 1917), 531.

This experiment is cited to show that oil does not migrate up the dip due to specific gravity differences, nor is it forced upward by circulating water.

On the outcrop the sands in the oil-bearing formations are not continuous but lenticular. By careful study of sands from well logs in different pools of the mid-continent field, the lenticular property of the sands becomes more evident. Water analyses

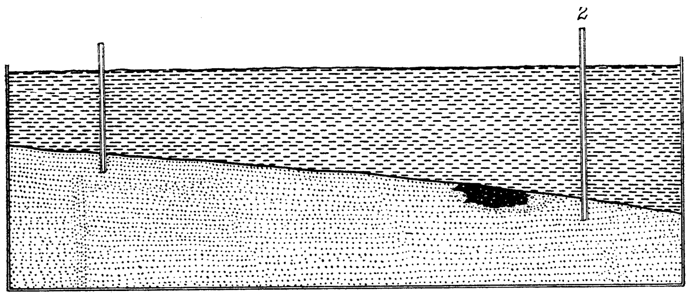


FIG. 5.—Diagram of apparatus for experiment showing no movement of oil in sand

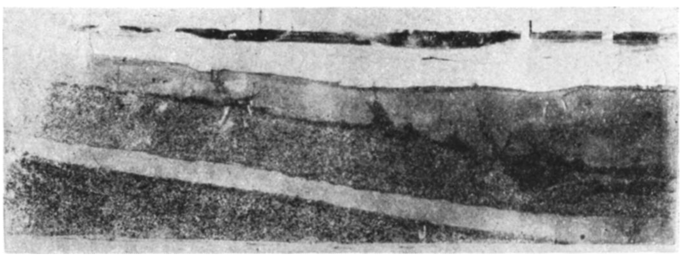


FIG. 6.—Photograph of apparatus used in Experiment 3, showing the oil remaining in the sand where it was originally placed.

also corroborate this fact. Results from four hundred water analyses to date point to the fact that each sand lens carries a definite water, uniform throughout and differing in some respect from the water of another lens. These waters are probably connate sea waters uncontaminated by surface water. In nearly pure silica sands the water differs little from sea water. In limy members or where other soluble minerals are noted the water is much higher in total solids than sea water. The present work seems to indicate that the change from normal sea water can be accounted for

by the minerals in, and surrounding, the water horizon. If the water shows no connection between different lenses in a sedimentary series, surely continuous sands or porous zones cannot be expected and consequently the analyses check the impossibility of migration from one lens to the other.

The pressure on the oil as it exists in the porous stratum is the same as that on the water which previously occupied the space. A volume of water replaces approximately an equal amount of oil, consequently the pressure in the reservoir remains the same. When the relation of oil to advancing water is such that the oil may be trapped and forced forward by capillary water, considerable pressure may accumulate on the oil due entirely to the capillary action of the water. Such conditions would be local if ever present and of little importance in commercial oil pools.

Pressures on fluid in an oil sand are often spoken of as "rock pressure" or "gas pressure." Neither term exactly defines the accumulated pressure on the fluid. The maximum static pressure available in any porous zone is a function of the size of the openings around that stratum. The determining factor is the capillary resistance of the water in the adjoining small openings. This factor depends upon the character of the sediment and the amount of compactness of the same. As the beds are more deeply buried, the shales become more compacted, and consequently the maximum available pressure in a given reservoir would be increased with depth. In this way there is a relation of maximum pressure to depth in the upper 10,000 feet of sediment. However, pressures do not necessarily increase with depth as would be indicated by the term "rock pressure." The amount of water originally in the reservoir and the tightness of the surrounding shales are other factors which may greatly change any relation of accumulated pressures to depths. A buried sand deposit may be completely filled with water and surrounded by a very fine shale, so that a small amount of settling[1] would increase

[1] In this paper it is assumed that settling of the strata has caused the fluid pressure in water sands of most of the mid-continent oil pools. With various degrees of saturation in sands of irregular sedimentation, the resulting fluid pressures after settling would be quite variable and irrespective of depth. Such is the case through-

the pressure on the water over that of a deeper sand, which might not have been so nearly saturated nor surrounded by so fine a shale.

The following estimate is made to show that the amount of oil in any producing field could have been derived entirely from shales immediately surrounding the oil sand. A series of shales aggregating 10 feet of bituminous sediment, yielding 25 gallons to the ton would furnish 17,000 barrels of oil per acre. Assuming a 25 per cent extraction, the acre yield would be over 4,000 barrels. The average acre yield in Oklahoma and Kansas ranges from 2,500 to 3,000 barrels. In case of 30,000-barrel-acre yield, which is a rare exception, the total amount of oil, considering a 25 per cent extraction, could be had from an acre bed of shale aggregating 50 feet of bituminous material yielding 40 gallons to the ton. Large acre yields are probably due to concentration in the sand along zones of exceptional openings, and the oil might have been drained from an area of several acres.

CONCLUSION

The foregoing evidence leads to the following conclusions:

1. Bituminous shales are in close relationship with the producing sand of an oil field.

2. This bituminous material is in solid form and is only changed to petroleum in local areas of differential movement.

3. After such a change is made, the accumulation of oil into commercial pools is accomplished by capillary water; and this interchange only takes place in local areas where the oil-soaked shale is in direct contact with the water of the reservoir rock. Such conditions are explainable either by joints or faults.

4. After the oil once reaches the sand, some adjustment takes place until the oil has found the larger openings and then it remains there indefinitely.

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out the Pennsylvanian rocks of Oklahoma, Kansas, and Texas. Moreover, in a number of cases the water may be reduced or exhausted by pumping the same as the oil, and the decline in production is according to the regular PV curve, showing that the pool is not connected with a source of supply, but has a definite volume in a definite space.

5. The amount of oil in any field could have been derived from normal bituminous shales in close proximity to the pay horizon.

6. These five statements also lead to another general conclusion, that areas of maximum differential movement are in accord with anticlinal structures. It has been noted from a study of the majority of pools in the mid-continent field that the maximum sub-surface faulting is found on the flanks and sides of the anticlines, and that the best production runs in trends parallel to the faulted zones. It has also been noted in a number of cases that production which is not related to marked anticlinal or dome structure bears the same close relation to sub-surface faults.[1]

The author is indebted to many co-workers in the sub-surface branch of the geology department of the Empire Gas and Fuel Company, who have diligently collected and compiled information. Especially is acknowledgment made to Mr. Gerald E. Moser for the diagrams in this paper; to Mr. E. A. Trager for aid in the experiments; to Dr. L. C. Snider for suggestions and criticisms in the work; and to Mr. Everett Carpenter, whose advice and counsel have made the investigation possible.

[1] Detailed data for the basis of these statements are necessarily considered confidential and cannot be published at this time. It is hoped that this material may sometime be available so that a paper discussing the details of various producing structures can be published.